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INVESTIGATION OF THE EFFECT OF PROCESS PARAMETERS ON MATERIAL REMOVAL RATE IN MACHINING OF IS 5986 FE 410 STEEL BY WIRE-EDM: THE OPTIMIZATION AND REGRESSION MODELING

D. DEEPAK[1] & B. RAJENDRA BEEDU[2]

[1]*Associate Professor, Department of Mechanical and Manufacturing Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education, Karnataka, India*

[2]*Professor, Department of Mechanical and Manufacturing Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education, Karnataka, India*

Original Article

ABSTRACT

Non-traditional machining methods are popular in the recent era for machining of various profiles in different engineering materials. In this work, the effect of critical process parameters, namely current (I_c), pulse-on time (T_{on}), pulse-off time (T_{off}), wire-speed (W_s) and voltage (I_v) on material removal rate (MRR) is investigated while machining of IS 5986 FE 410 steel by wire-electrical discharge machine (wire - EDM). The experiments were designed using Taguchi L_{16} arrays and results are analysed using statistical methods. The process parameters such as T_{off}, I_c and W_s showed significantly the contribution by 54.17%, 22.08% and 13.77%, respectively, on MRR. Further, the process parameters were optimized obtaining higher MRR which yielded 1.23 mg/s at settings I_c -5A, t_{off}-40 µs, T_{off}-5 µs, W_s - 1400 rpm and I_v - 90 V. Regression model is developed to predict the MRR with the control parameters with R^2 values 89.30%. The model predicting accuracy of the model is verified by the confirmation experiments.

***KEYWORDS:** Wire-EDM, Material Removal Rate, Pulse-Off Time, Current, IS 5986 FE 410 Steel, Wire Speed, Pulse-On Time & Voltage*

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1. INTRODUCTION

The rapid changes in the market scenario demand the steels with enhanced quality, properties and performance capabilities to suit the design specification of the end products. Alloys of steel possess superior mechanical properties such as corrosion resistance, [1-2] good hot workability and high toughness, which made the material suitable for structural applications. In general, steel alloys are used in various applications including automobiles, shipbuilding, boiler and pressure vessels, transmission towers, railways, oil and petrochemicals, coal and mining, general and heavy engineering machinery parts, etc. Machining of steel is challenging due to high affinity of work hardening, high toughness, low thermal conductivity and high fracture toughness.[3-6] Materials such as duplex stainless steel show the tendency for the formation of built-up edge. The adherence of material to cutting tool reduces the cutting speeds, which affect the machining efficiency in the form of accelerated tool wear, poor surface finish and low-dimensional accuracy.[7, 8] Although some of the complexities involved in conventional machining may be addressed by the non-traditional machining methods, there is limited literature available on machining characterization of steel and its alloys.

Raghavan *et al.*[9] attempted laser tempering-based turning process for machining of hardened AISI 52100 steel, which is used for large wind turbine bearing. Initially, the hardened work piece surface was laser

tempered and then conventional machining was made. The study showed that this method resulted in lower cutting forces and tool wear rate, higher material removal rate (MRR) compared to conventional hard turning. Alshemary[10] studied the different types of errors generated on cylindrical holes while machining 2205 duplex stainless steel fabricated by the wire-electric discharge machining (EDM). Interactions between process parameters were found to significantly affect the diameter errors such as circularity and cylindricity. These errors are produced by non-uniform undercut and overcut, which are controlled by settings to input parameters. Gamage *et al.*[11] studied the process level environmental effect of EDM process settings on machining performance of aluminium (3003) and steel (AISI P20) through time, energy, resources and emissions studies for each case. A considerable amount of energy consumption was found to occur during non-productive machining stages, which particularly show the impact on the environment in the form of consumption of electrical energy (60%). Deepak D *et al*.[12] optimized the current and pulse duration in electric discharge drilling of D2 steel using graphite electrode. The study shows that MRR and surface roughness was significantly influenced by the current. The optimum settings produced MRR 38.16 mg/min and surface roughness of 3.39 μm. Morphology of the cut surface showed the formation of globules due to machining. Further, the coefficient was established for predicting surface roughness for machining this material by EDM.13 The authors also investigated the influence of abrasive water jet machining of D2 heat-treated steel.[14] It was found that at constant standoff distance (SOD), the top kerf width was increased by 18% and the bottom kerf width was decreased by 25% due to increase in jet pressure in one pass machining. Further, surface roughness was also found increased at higher SOD and feed rate. Zhu *et al.*[15] studied the surface quality of stainless steel produced by blasting erosion arc machining. The results showed that the negative beam resulted in producing a highly rough surface (up to Ra - 55 μm), the heat-affected zone (HAZ) to depth about 13 μm from the machined surface and the formation of recast layer. The positive beam resulted in good surface finish (Ra 9.5 μm), the HAZ was lesser at 5 μm and minimization of the recast layer. Klocke *et al*[16] investigated the Electrochemical Machining of 42 CrMo4 Steel by numerical methods. The study detailed the microstructure evolution process on surface topography in a passivating electrolyte system. The model helps to predict the surface topography for different process parameters and various initial microstructures.

This work investigates the effect of current, pulse-on time, pulse-off time, wire-speed and voltage on MRR while machining of IS 5986 FE 410 steel by wire EDM and optimizes the settings. Also, based on the experimental results, a mathematical model is developed to predict the MRR for different input settings of the process parameters. This work is expected to help wire-EDM industries to choose the optimum settings for machining of IS 5986 FE 410 grade steel by wire EDM.

2. MATERIALS AND METHODS

2.1 Experimental Setup and Specimen Details

Figure 1 shows the details of experimental setup. In the present work, experiments are performed using a 2-axis (X-320 mm, Y-400 mm) computer numerically controlled wire-EDM made by Concord wire-EDM, India (Model DK7732). Molybdenum wire (diameter: 0.16 mm) is a used tool electrode during the experiments. Mixture of soft water and gel is used as dielectric fluid. The resolution of the controller is 0.001 mm. The work piece used is IS 5986 Fe 410 steel. The chemical composition and mechanical properties of the work piece is shown in Tables 1 and 2, respectively. The carbon equivalent (CE) is determined based on ladle analysis as given by Equation (1).

$$CE = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15} \tag{1}$$

Figure 1: Experimental Setup.

Table 1: Chemical Composition

Carbon	Manganese	Phosphorus	Sulphur	CE
0.20	1.50	0.035	0.035	0.45

Table 2. Mechanical Properties

Yield Strength	Ultimate Tensile Strength	Elongation
420 MPa	480 - 5 90 MPa	15%

2.2. Design of Experiments

The process parameters such as current, pulse-on time, pulse-off time, wire speed and voltage are chosen to study its effect on MRR. The voltage is varied at two different levels and remaining parameters are varied at four different levels. Table 3 shows the process parameters and their levels. These levels are chosen based on the trial experiments. Total degree of freedom required for the experimental design is 13, hence experiments are designed using L_{16} (4^5x1^2) Taguchi orthogonal array. Table 4 shows the experimental design. The experiments were replicated for two trials in each experimental condition. Thickness of specimens (5 mm) and the supply pressure of dielectric fluid were kept constant during experiments.

Table 3: Wire-EDM Process Parameters and their Levels

Parameters	Unit	Code	Level 1	Level 2	Level 3	Level 4
Current	A	I_c	3	4	5	6
Pulse-on time	μs	T_{on}	20	30	40	50
Pulse-off time	μs	T_{off}	5	10	15	20
Wire speed	RPM	W_s	175	350	700	1400
Voltage	V	I_v	80	90	-	-

Table 4. The Experimental Design and Corresponding Average MRR (mg/s)

Trial no	Settings of the Process Parameters					Average Response	
	I_c	T_{on}	T_{off}	W_s	I_v	Machining Time (s)	MRR
1	2	10	5	1400	80	100	0.730
2	2	20	10	700	80	143	0.552
3	2	30	15	350	90	208	0.385
4	2	40	20	175	90	371	0.208
5	3	10	10	350	90	116	0.629
6	3	20	5	175	90	109	0.569
7	3	30	20	1400	80	210	0.357
8	3	40	15	700	80	166	0.482
9	4	10	15	175	80	180	0.406
10	4	20	20	350	80	214	0.379
11	4	30	5	700	90	77	1.104
12	4	40	10	1400	90	88	0.943
13	5	10	20	700	90	140	0.529
14	5	20	15	1400	90	107	0.757
15	5	30	10	175	80	133	0.602
16	5	40	5	350	80	78	1.141

2.3. Measurement of Response

Test samples are machined for a length of 20 mm as per the experimental design shown in Table 4. The weight of the workpiece before and after the machining is measured using digital mass balance (accuracy: 0.001 g). The MRR obtained for each experimental trial is calculated by weight loss method. Table 4 also shows the average MRR obtained in different experiments. The cut surfaces of test samples machined at different settings of process parameters is shown in Figure 2.

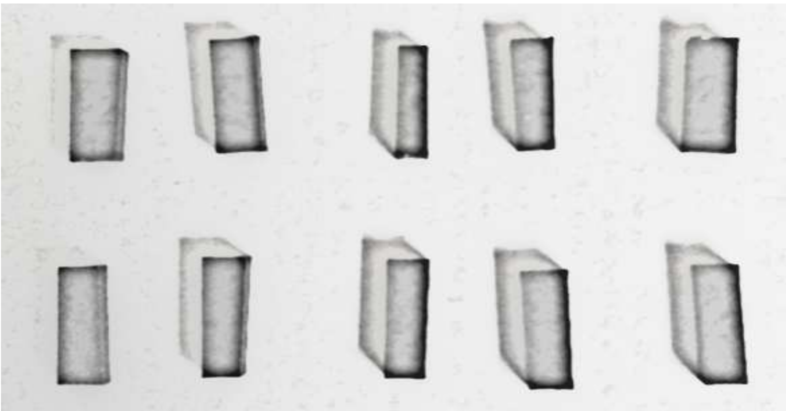

Figure 2: Cut Surface of the Machined Samples.

3. RESULTS AND DISCUSSIONS

3.1. The Effect of Process Parameters on MRR

Figure 3(a) shows the influence of current on MRR. It is observed that the MRR is increased with increase in current from 2 A to 5 A. An increase in current level from low to high increase the breakdown voltage and raises its spark energy. Hence, high current results in melting and vaporization of more volume of material from workpiece, which led to an increase in MRR. Figure 3(b) shows the effect of pulse-on time on MRR. It is observed that the increase in pulse-on time from 20 μs to 40 μs increased the MRR almost linearly. The energy (E) of each spark is given by $E = I_v I_c T_{on}$. This indicates that the longer spark duration (pulse-on time) release the more amount of spark energy in each spark cycle. Hence, the increase in pulse-on time resulted in increasing MRR.

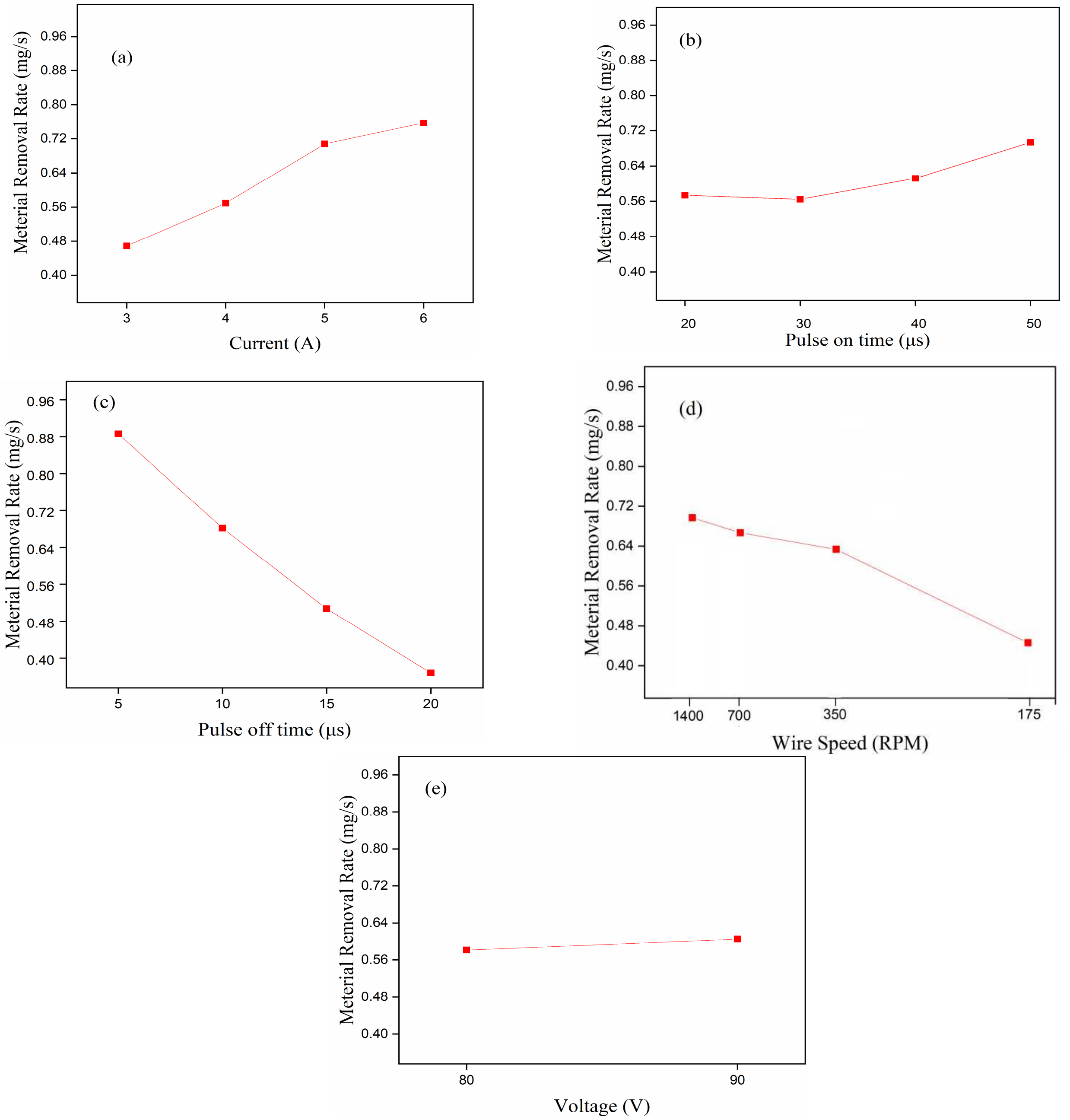

Figure 3: The Effect of Process Parameters on MRR.

Interestingly, an increase in the pulse-off time from 5 μs to 20 μs is found to be counterproductive which resulted in a steady decrease of MRR, as shown in Figure 3(c). Pulse-off time is the time duration at which sparking does not occur. Increasing the pulse-off time increased the cycle time and thus reduced the spark frequency. This resulted in decreasing the MRR with an increase in pulse-off time. Further, it is observed in Figure 3(d) that the MRR increased with an increase in the rotational speed of drum on which the electrode wire rotates. The MRR is observed to be improved sharply due to an increase in drum rotation speed from 175 RPM to 350 RPM. Further increase of drum speed up to 1400 RPM also resulted in improving the MRR, but at a different rate. Figure 3(e) shows the effect of voltage on MRR. It is observed that MRR is directly proportional to voltage. As explained earlier, the spark energy is a function of voltage, current and pulse-on time (i.e., $E = I_v I_c T_{on}$). Hence, higher voltage resulted in melting and

vaporization of greater volume of material, which led to an increase in the MRR. The MRR is increased by 9.23% with an increase of voltage from 80 V to 90 V in the spark gap.

3.2 Analysis of variance (ANOVA) of MRR

The results of ANOVA of the MRR is shown in Table 5. The F-test is conducted on the ANOVA data at 95% confidence level to identify process parameters, which are significantly affecting MRR. The F-values of the current pulse-off time and wire-speed are found to be higher than the critical values and hence their effect on MRR is significant for the chosen range of settings to the operating parameters. Further, the percentage contribution of each process parameter is calculated. The pulse-off time is the most significant parameter that contributed maximum (54.17%) to variation of MRR followed by current (22.08 %) wire speed (13.77 %), voltage (3.81%) and pulse-on time (3.75 %).

Table 5: Analysis of Variance for MRR.

Source	DF	Seq SS	Adj MS	F
Current	3	0.2452	0.08173	9.07
Pulse-on time	3	0.0416	0.01386	1.54
Pulse-off time	3	0.6016	0.20054	22.26
Wire speed	3	0.1529	0.05099	5.66
Voltage	1	0.0141	0.01409	1.56
Residual Error	2	0.0180	0.00900	
Total	**15**	**1.0735**		

DF: degree of freedom, MS: mean square, SS: sum of square

3.3 Optimum of Process Parameters

Taguchi method is adopted for the optimization of machining settings, which produce maximum MRR while machining of IS 5986-Fe410 by wire-EDM. Table 6 shows the average MRR obtained at different settings of process parameters. From the table, it is observed that the maximum MRR is achieved at the settings, $A_4B_4C_1D_1E_2$, i.e., current: level 3 (5A), pulse-on time: level 3 (40 μs), pulse-off time: 5 μs (level 1), drum/wire speed - level 4 (1400 rpm) and voltage - 90 V (level 2). The predicted MRR at this setting is 1.23 mg/s. The confirmation experiments are conducted and test results are shown in Table 5. It is seen that MRR obtained by the experiments is in agreement with the predicted MRR with maximum error of 6.93%. The maximum change (delta) in MRR due to change in settings of different process parameters at different levels is also shown in the same table. Based on the delta values, the process parameters are ranked in the order of their influence as pulse-off time: I, current: II, wire speed: III, pulse-on time: IV and voltage: V.

Table 4: The Average MRR

Level	Current	Pulse-On Time	Pulse Off Time	Wire Speed	Voltage
1	0.4687	0.5734	0.8859	0.6968	0.5810
2	0.5093	0.5642	0.6816	0.6667	0.6404
3	0.7078	0.6118	0.5073	0.6334	
4	0.7570	0.6934	0.3679	0.4459	
Delta	0.2884	0.1292	0.5180	0.2510	0.0594

Table 5: The Predicted and Experimental MRR at Optimum Conditions

Trial	Predicted	Experimental	%Error
1	1.23	1.157	5.90%
2	1.23	1.152	6.37%
3	1.23	1.180	4.10%
4	1.23	1.145	6.93%

3.4. Regression Modelling of MRR

A mathematical model is developed to establish relationship between the process parameters (x_1: Current, x_2: Pulse on time, x_3: Pulse off time, x_4: wire speed, x_5: voltage) and the response parameter, that is, MRR. The main effect of process parameters is considered in the modeling. The developed regression models are by Equation (2), the coefficients of determination (R^2) for the fitted regression equation is 89.30%. The predicting accuracy of regression model is tested by conducting confirmation experiments within the range of operating parameters, that is, $3 \geq x_1 \leq 6$; $20 \geq x_2 \leq 50$; $5 \geq x_3 \leq 20$; $375 \geq x_4 \leq 1400$; $80 \geq x_5 \leq 90$. The distribution of residuals is shown in Figure 4. It is observed that the residuals are distributed around the line of fit, linearly. The MRR predicted by regression model and the experiments are shown in Figure 5.

$$MRR = -0.039 + 0.1064 \times I_c + 0.00408 \times T_{on} - 0.03457 \times T_{off} + 0.000158 \times W_s + 0.00594 \times I_v \quad (2)$$

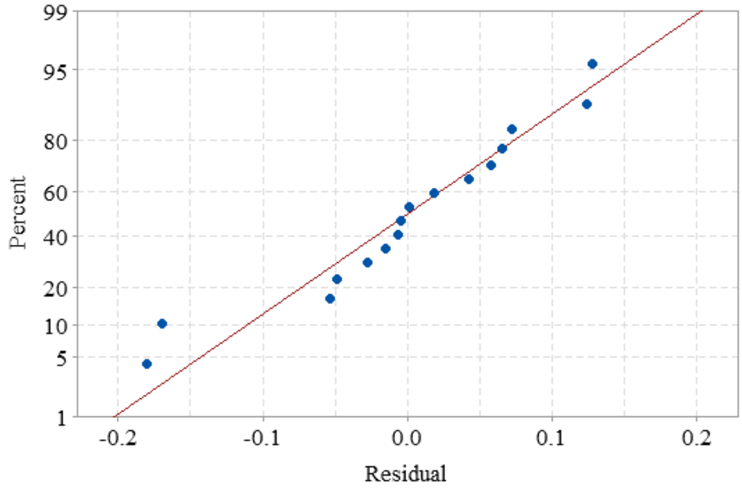

Figure 4: Distribution of Residuals.

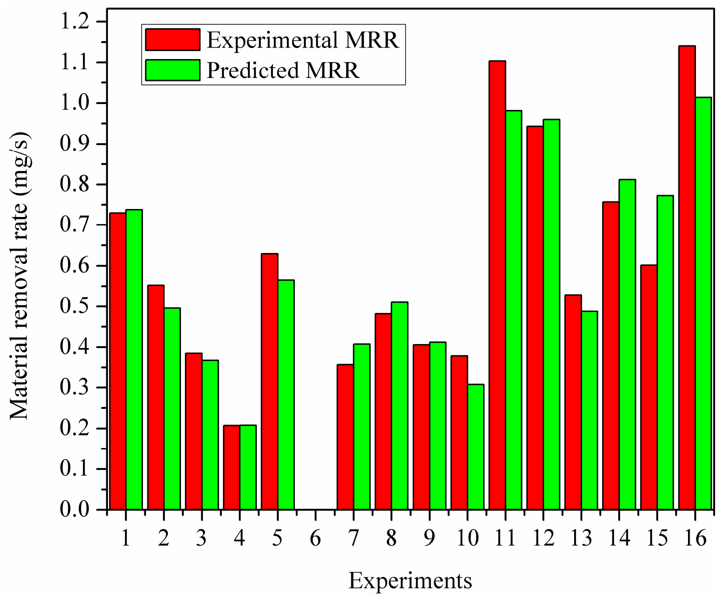

Figure 5: Comparison of MRR Predicted by Regression Model with Experiment Values.

4. CONCLUSIONS

Based on the wire-EDM of IS 5986 Fe 410 steel, the following conclusions are drawn:

- The process parameters such as pulse-off time, current and wire speed showed significant influence on MRR. The contribution of process parameters on MRR are the pulse-off time - 54.17%, current - 22.08%, wire speed - 13.77%, voltage - 3.81% and pulse-on time - 3.75%.
- The optimum settings which produced the maximum MRR (1.23 mg/s) are current -5A, pulse-on time - 40 μs, pulse-off time -5 μs, wire speed - 1400 rpm and voltage - 90 V.
- The regression models are developed to predict the MRR within the operating range (3 A $\geq x_1 \leq$ 6 A; 20 μs $\geq x_2 \leq$ 50 μs; 10 μs $\geq x_3 \leq$ 25 μs; 375 rpm$\geq x_4 \leq$ 1400 rpm; 80 V $\geq x_5 \leq$ 90 V) with R^2 values 89.30%. The model predicting accuracy is verified by the confirmation experiments.

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AUTHOR'S PROFILE

Deepak D. is Associate Professor in the department of Mechanical and Manufacturing Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education, India. He has obtained B.E (2003), M. Tech (2005) in Manufacturing Engg. from National Institute of Engineering, Mysore and Ph.D from Manipal University, India. His area of research includes CFD analysis and advanced manufacturing process. He has published about 20 international journal and conference articles. He has received a certificate of merit for his research article in World Congress of Engineering 2012 held at Imperial college, London, UK. He is a member of International Association of Engineers (IAE).

Dr Rajendra Beedu is Professor in the department of Mechanical and Manufacturing Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education, India. He has obtained Ph.D from NIT, Suratkal, India. His area of research includes manufacturing process and mechanical Vibrations. He has published about 28 international journal and conference articles. He has about 35 years of teaching experience and published one text book on Engineering Graphics.